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SUCTION FORCE IN SOILS UPON FREEZING

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SUCTION FORCE IN SOILS UPON FREEZING

Alfreds R. Jumikis,[1] M. ASCE

SYNOPSIS

The intent of this article is to describe and to stimulate interest in the problem of suction of soil moisture upon freezing. This problem is of great technical and economic concern to highway and airport engineers. In the thermo-osmotic process, inaugurated after a freezing thermal gradient is commenced, suction is considered as the driving force for the upward flow of soil moisture to the growing ice lenses.

A simplified method for the calculation of the suction force is displayed. Examples of the practical application of the suction head are mentioned. Indication is given of small scale pilot tests now in progress on measuring suction heads in soil upon freezing.

INTRODUCTION

General Notes

Among other factors entering into highway substructure design, the factor "frost" is a significant one. Frost action may cause local heaving of road and runway pavements, subsequent softening of pavement-supporting soil during thawing periods, and localized settlements. This, in turn, creates rough riding surfaces, and can cause heavy damage to rigid and flexible pavements as well as to unpaved roads.

In dealing with the frost problem in highway engineering, we are interested in (1) the depth to which frost penetrates the various soils; (2) the intensity and duration of the cold weather period; (3) the geotechnical and thermal properties of the soil; (4) the position of the ground water-table and proximity of other water sources with respect to the pavement. However, in addition, attention should also be directed to (5) the phenomenon of how the soil moisture is supplied to the growing ice lenses, and (6) the question of the driving force causing the migration of moisture toward a cold isothermal boundary surface and inaugurated by a freezing thermal gradient.

The simultaneous conditions necessary for the formation of ice lenses in a soil within a freezing zone are: (1) the soil itself, (2) freezing temperatures, and (3) moisture and its affinity to a soil with thermal changes. In particular, the cyclic variations in freezing and thawing temperatures and in moisture content of the soil under the pavement are to be considered the most destructive factors. Briefly, traffic loads, climatic factors and frost-susceptible soils, mainly silts (see References 4, 15), are responsible for a great deal of the destruction of our highways.

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The Thermo-Osmotic Phenomenon

Experience indicates that the capillary tube (meniscus) theory and some opinion about "condensation" and accumulation of soil moisture underneath a highway pavement during the night are inadequate to explain the supply of soil moisture in an open system for the growth of ice lenses upon freezing. An important phenomenon in the formation of ice lenses in soil upon freezing is the upward flow of soil moisture from the ground water toward the growing ice lenses (Fig. 1).

An upward flow of soil moisture is inaugurated after a proper thermal gradient has commenced at the bare or covered ground surface. Generally, in northern regions thermal gradients in winter cause an upward flow of soil moisture (bare soil or pavement) and a downward flow in summer. The soil moisture migrates then in the direction of the flow of heat, i.e., from warmer region to a colder one. This results in the accumulation of the soil moisture under the pavement. There, under optimum conditions, the soil moisture saturates and softens the subgrade, thus decreasing its bearing capacity, which,in turn, causes the destruction of the pavement. At freezing temperatures, this moisture freezes, causes heaving, and upon thawing may be the cause of damage to roads (13, 14, 15, 16, 17).

Although the process of moisture migration is slow, a considerable amount of soil moisture can flow upward during a relatively long period of time under a thermal gradient. However, it is the slow process of flow which often is overlooked and forgotten, and which is one of the main factors in the thermo-osmotic phenomenon where the danger of damage to highways and runways lies. Therefore, the problem of moisture supply from the ground water table to the growing ice lenses at a freezing thermal gradient should be of particular concern to the highway engineer.

The phenomenon of moisture migration in porous systems, inaugurated by a thermal gradient, is called thermo-osmosis (5, 16, 17, 18). Because of its importance, we should be interested in performing large scale experimental research to prove the practical significance of thermo-osmosis in highway engineering. However, large scale research is often prohibitive in cost. This, and also the difficulty involved in treating this problem as a thermal system, explain partially why hitherto very little large scale research has been made in the field of thermo-osmosis.

The Problem

Because of the reasons just mentioned, the author assumed the task of trying to display the suction force problem from a practical aspect. The problem in this task is: based on several assumptions as outlined in the next chapter, to calculate by simple means the suction force causing the upward flow of soil moisture upon freezing.

The author realizes that in such a treatment of the subject many factors are masked out. For example, the combination of the conduction of heat upward from the bottom of the growing ice lenses and the heat set up free (latent heat of fusion) when moisture is converted into ice, the heat carried up by the ground water by means of suction, together with the amount of moisture moved, all seem to be of basic importance, yet they are masked out. However, it is believed that this approach to the subject will give at least a general insight into this matter. Assumptions, which later might prove inadequate, can then be corrected as our knowledge increases.

Upward Flow of Soil Moisture

Assumptions

In treating the problem of suction force in soils upon freezing, the following assumptions are made:

1. There is a ground-water source present, at a certain distance below the ground or pavement surface;
2. In the process of suction the soil is fully saturated with held moisture, and there is no excess moisture in the soil which might disturb the suction process;
3. The upward flow of moisture takes place in the liquid phase unidimensionally;
4. The vapor movement in the soil is negligible, and therefore ignored;
5. The moisture transfer between the soil and the atmosphere is negligible;
6. Upon the application of a freezing thermal gradient, a hydraulic gradient or suction is inaugurated, causing an upward flow of moisture toward the growing ice lenses within the stressed moisture film adsorbed to the soil particles;
7. A growing ice lens is in direct contact with a thin hull or film of soil moisture similar to the adsorbed layers which form on many other solids that are in contact with water, permitting it to pull up and supply the necessary moisture for the growth of ice lenses;
8. Moisture in soil freezes at 32° F. Factors which may affect the freezing point of soil moisture, such as salinity, are ignored;
9. The moisture system treated here is an open system, i.e., one such as we find in the field, where additional moisture can enter and be sucked up vertically into an imaginary vertical prism as a result of freezing, on the application of a freezing thermal gradient.

Upward Flow

It can be understood that, in order that an upward flow of soil moisture upon freezing may exist, a certain potential or hydraulic gradient is necessary. Such a hydraulic gradient can exist only because of a prevailing subpressure (below atmospheric pressure) in the adsorbed pore moisture films of the soil.

It has very often been a question whether this subpressure as a driving force is a consequence of the open curved capillary menisci, or whether the driving force can be considered as being a function of some kind of a suction caused by the withdrawal of moisture from the films surrounding the soil particles after freezing has commenced.

There are several schools of thought in this matter. The Swedish school supports capillarity as being the driving force for the upward flow of soil moisture upon the application of a thermal gradient (1, 2), whereas some scientists of the American school of thought (3, 7, 11, 12, 13, 14, 17, 18), and recently also some European scientists (5, 6, 8, 9, 10) support the so-called "Suction Force Theory."

The following is the objection against the capillary force theory. One has to assume that on freezing, the lower boundary of the ice lens, or of the frozen layer of soil, is in direct contact with the upper boundary (menisci) of the capillary soil moisture. Also, it is understood that the capillary forces are present only then, that is, when there are open or free-surface menisci present which form a moisture-air boundary. Therefore, it is difficult to imagine how a surface of free menisci at the lower ice boundary can be formed, and, at the same time, capillary subpressure developed. This inconsistency has

been pointed out already by Taber (11, 12).

British research workers (5, 6, 8, 9), under the direction of D. J. Mclean, Head of the Soils Section of the Road Research Laboratory, Department of Scientific and Industrial Research, Hermondsworth, Middlesex, England, have been engaged in soil suction studies in connection with solving practical problems in military and airfield construction at home and in their possessions. They attribute the movement of soil moisture exclusively to suction on the principle of thermo-osmosis similar to the treatment given in this paper.

It seems as if the British authors, as here cited, because of the objections already mentioned to capillarity as the driving force, in dealing with moisture movement in soil, intentionally and rightly do not use the term "capillarity." The British studies are accentuated mostly on suction-moisture content relationship of various soils beneath impervious pavements under moisture equilibrium conditions, as well as subjected to thermal gradients. However, their work differs from that treated in this paper in that they worked with warm thermal gradients (above freezing) at moisture and suction equilibrium. Thus far frost has not been taken into consideration in their works. In this paper, however, the suction force is treated at freezing thermal gradients which cause the building up, under the pavements, of layers of segregated ice. This difference might be explained by the necessity for studying immediate problems as they arise in the various climatic regions.

Existence of the Suction Force

If, as in Soil Mechanics, we presuppose that a soil particle is surrounded by a film of adsorptive moisture, then we have to accept that in such a film of moisture there exists a comparatively large amount of adsorptive forces (3,16). By means of these forces, the moisture in the film is stressed. The formation of ice crystals can take place by sucking up of the moisture from the moisture film. On freezing, by releasing heat, the ice crystal is able to attract water molecules from the external, weakly-bound hull of the stressed film and to attach them to the ice crystal. Because of this, the water, drawn away from the film, is replaced by another molecule by pulling it out of the neighborhood in order to reestablish the integrity, i.e., the equilibrium between the adsorption forces and the external pressure in the moisture film (see Fig. 2). Thus, a molecular upward flow of soil moisture, i.e., an upward suction of moisture, in the liquid phase, from the unfrozen pores toward the growing ice crystal takes place. Any variation in soil moisture content at any point, located within the soil between the ground water-table and pavement, or ground surface, and originally at moisture equilibrium, causes a potential or suction gradient of soil moisture at that point, and virtually unaccompanied by vapor pressure. This suction continues until all of the soil moisture is consumed, or until the constantly freezing soil layer has grown in thickness and reached the ground water-table, or when the freezing process is checked by an increase in temperature, i.e., the moisture redistributes and a new state of suction equilibrium is again attained.

Because the formation of ice crystals is also possible on excluding capillarity fully (overflooding the soil sample), the suction force theory seems to be plausible and has a satisfactory explanation of the phenomenon of the upward flow. Therefore, for practical purposes it may be expedient to simply accept the suction force caused by a reduced pressure in the moisture films in the soil on freezing as a property of a soil.

Definition of Suction Force

Assume that the frost heave, Δh, corresponds to the volume of the soil moisture, V, sucked up during a period of time, t, from groundwater toward the ice lenses. Then, taking into consideration the expansion of ice, the volume of soil moisture is

$$V = \frac{(A)\cdot(\Delta h)}{1.09} \qquad \left[\text{in.}^3\right], \qquad (1)$$

where A = area of horizontal section of the soil or soil sample through which the upward unidimensional flow takes place. The volume, V, of moisture moved can be computed analytically (18), or determined experimentally. The rate of this upward flow is

$$Q = \frac{V}{t} = \frac{(A)\cdot(\Delta h)}{(1.09)\cdot(t)} \qquad \left[\text{in.}^3/\text{sec.}\right], \qquad (2)$$

where t=time during which an upward flow is tested; also duration of the frost period. The actual average suction velocity of this flow is

$$v = \frac{Q}{A} = \frac{(\Delta h)}{(1.09)\cdot(t)} \qquad \left[\text{in./sec.}\right]. \qquad (3)$$

Assuming

1. that the upward flow of moisture is not affected by gravity, and
2. that therefore for this upward flow the suction velocity is directly proportional to the suction gradient, i, which is necessary to maintain the upward suction caused by a suction head, h_s,

$$v = k_s \cdot i, \qquad \left[\text{in./sec.}\right], \qquad (4)$$

where

k_s = coefficient of proportionality of vertical flow through the soil concerned, or simply--suction coefficient (an experimental coefficient, not to be confused with Darcy's law of permeability of liquids through a porous medium for gravitational flow). The suction coefficient k_s is the actual average velocity of the upward flow when i=1.0. Winterkorn suggests calling this coefficient a "coefficient of thermo-osmotic permeability" (18). It is defined as "the amount of water moved in unit time through a cross-section of 1 cm^2 of the soil-water system under a thermal gradient of 1 degree C. per cm." It can also be calculated analytically from energy considerations.

The suction head, h_s, expressed in column of water, is:

$$h_s = \frac{P_s}{\gamma_w} \qquad \left[\text{in.}\right]. \qquad (5)$$

Here,

P_s = subpressure, real or fictive, in lb./$in.^2$, and
γ_w = unit weight of water, in lb./$in.^3$.

Hence, the suction gradient can be expressed as follows:

$$i = \frac{\text{suction head}}{\text{suction height}},$$

or

$$i = \frac{\left(\frac{P_s}{\gamma_w}\right)}{L}. \qquad (6)$$

The suction height (or filtration length), L, is the distance from the ice lens to the ground water-table (see Fig. 1).
Substituting Eq. (6) into Eq. (4), we obtain

$$v = k_s \cdot \frac{P_s}{\gamma_w} \cdot \frac{1}{L} \qquad (7)$$

From here, the subpressure is:

$$P_s = \frac{\gamma_w}{k_s} \cdot L \cdot v = \frac{\gamma_w \cdot (\Delta h) \cdot L}{(1.09) \cdot (k_s) \cdot (t)}, \qquad (8)$$

and the suction head can be expressed as follows:

$$h_s = \frac{P_s}{\gamma_w} = \frac{L \cdot v}{k_s} = \frac{(\Delta h) \cdot L}{(1.09) \cdot (t) \cdot (k_s)}. \qquad (9)$$

If the depth of the ground water-table below the road or soil surface is designated by H, and the frost penetration depth by ξ, then the suction length, L, can be expressed as

$$L = H - \xi \quad . \qquad [\text{in.}] \qquad (10)$$

$$P_s = \frac{(\gamma_w) \cdot (\Delta h) \cdot (H - \xi)}{(1.09) \cdot (k) \cdot (t)}, \qquad (8a)$$

$$h_s = \frac{(\Delta h) \cdot (H - \xi)}{(1.09) \cdot (t) \cdot (k_s)} \qquad (9a)$$

Equations (8) and (8a) define the subpressure, and Equations (9) and (9a) the suction head.

Thus, the suction force can be defined as follows:

By a suction force is understood the maximum possible subpressure, P_s, to which the pore moisture of the soil, upon freezing, is subjected in order to cause an upward flow towards the ice lenses. The subpressure is inaugurated by the freezing temperatures, and is to be measured at the downwards progressing, ice-forming isothermal boundary. Of course, the amount of the frost heave is also a function of the external pressure, or surcharge (for example, weight of pavement) (7).

Analysis of the Subpressure Function

From Equations (7), (8a) and (9a) one can see that both the upward flow of soil moisture and the suction force of a soil under freezing conditions are a function of the position of the ground water-table, H, the frost penetration depth, ξ, the permissible frost heave (practically $(\Delta h)_{max} \leq 2$ in. over a certain riding length, but for frost susceptible soils, rigid pavements, and high speed travel, even this is too much), and the coefficient of the thermo-osmotic permeability, k_s, of the soil at or near freezing temperatures. The suction length, according to this theory, is always

$$L_s \leq (H - \xi) \, . \qquad (11)$$

1. The Factor Frost Heave

When there is no flow (at the beginning of freezing v=o), P_s is likewise zero.

(a) When both, ($\triangle h$) and t, are zero (the very beginning of the freezing), P_S becomes undetermined. Thus, Eq. (8a) is valid, or P_S is real, for $t>o$ only.

(b) As time t passes, frost penetrates the soil and the frost heaving starts to develop, usually some time later after the freezing had started. This lag occurs because the timely course of the frost penetration depth depends primarily upon the thermal conditions of the soil and relatively less upon the upward moisture supply. Thus, at $\triangle h=o$ the suction force is zero because it takes some time to inaugurate upward suction of the soil moisture.

The amount of frost heave ($\triangle h$)cannot become infinitely large because the frost heave is checked when the source of moisture is expended, or when the frost penetration depth, ξ, reaches the ground water-table and the suction process ceases ($v = o$) (suction equilibrium condition established), or when a temperature change checks the formation of ice lenses. Therefore, P_S is real when

$$\infty > (\triangle h) \geq 0, \qquad t > 0 . \tag{12}$$

2. The Factor Suction Length

This case should be interpreted as follows: the greater the suction length, the greater P_S is needed. Therefore, P_S is real when

$$\infty > (H - \xi) \geq 0 . \tag{13}$$

Besides, the physical conditions do not permit an infinitely large suction length, nor an infinitely large suction force. Further, $H - \xi = o$, when the frost penetration depth, ξ, has reached the position of the ground water-table. Then $H = \xi$, the suction process ceases, and $P_S = o$.

3. The Factor "Suction Coefficient." k_S (thermo-osmotic permeability)

The greater k_S is, the smaller becomes P_S, i.e., the more porous the soil, the smaller suction force is needed. When $k_S = o$, there is no upward flow, which implies that P_S cannot be infinity. On the other hand, indeed, physically k_S is always far less than infinity. Therefore, P_S is real when

$$\infty > k_s > 0 . \tag{14}$$

4. The Factor "Time"

It is obvious that P is real when $\infty > t > O$. Within these limits, the greater t is, the less P_S becomes. It is because with increasing frost penetration depth, ξ, the suction height, L, decreases; this requires gradually less and less suction force. At some finite $t<\infty$, when $\xi = H$, the suction height is zero, and also P_S is zero.

Practical Applications

(1) In the instance that moisture conditions in a subgrade are such that the frost penetration depth intercepts the upward sucked soil moisture, frost damage to the road may occur. Should it be decided to remedy this situation by lowering the ground water-table, naturally the following question arises: what should the minimum distance, $L_{S_{min}}$, between the lowered ground water-table and the lower boundary of the maximum frost penetration depth be?

The idea of lowering the ground water-table is to pull down the suction height, L_S, so far that it will not be intercepted by the penetrating frost (see Fig. 3).

Numerically, by applying the suction force theory, $L_{S_{min}}$ can be solved by means of Eq. (8):

$$L_{s_{min}} = (1.09) \cdot (k_s) \cdot \left(\frac{P_s}{\delta_w}\right) \cdot \left(\frac{t}{\Delta h}\right) , \qquad (15)$$

where

$\frac{P_s}{\gamma_w}$ = suction head to be determined experimentally as a function of k_s at proper temperatures,

t = the duration of the frost period, and

Δh = the permissible frost heaving over a certain riding length which depends upon the type of soil and the pavement of the road.

This calculated $L_{s_{min}}$ should be checked against the actual conditions in the locality. If the maximum frost penetration in a particular soil is known (experienced or determined in the laboratory), and the position of the highest fluctuating ground water-table is from the frost penetration depth distant less than the calculated $L_{s_{min}}$, the ground water-table should be lowered accordingly until its position is distant $L_{s_{min}}$ below the frost penetration depth.

(2) Another practical application of the suction head is its use for the calculation of the frost penetration depth by means of the Ruckli formula as a function of (1) climatic conditions, (2) distance of the ground water-table from the ground surface, (3) geotechnical properties of soil, (4) thermal properties of soil, (5) pavement thickness, (6) thermo-osmotic permeability and (7) certain physical properties of ice (7).

From the foregoing treatment of the suction force theory, it can be seen that the distance of the ground water-table below the road or ground surface, H, the suction coefficient (thermo-osmotic permeability) of the soil, K_S, the climatic conditions causing frost penetration, ξ, and frost heave, (ΔH), a sufficiently long enough lasting freezing period, and certainly also the geotechnical and thermal properties of the soil and salinity of water, the effect of which here in this presentation is masked, are very important factors to be considered in dealing with the frost penetration problem in highway engineering.

It seems that the suction force, inaugurated on freezing, would be an important soil constant. However, more observations are needed in this field, and, of course, more studies should be devoted to the properties of moisture films in soils under various conditions, as well as to the problem of how moisture molecules are attached to the ice crystals.

Suction Measurements

Apparatus

In order to check whether a suction in a soil upon freezing can be measured in terms of a suction head, an apparatus was built (see Fig. 4). It consists of an insulated box into which a soil sample was placed. A freezing thermal gradient can be applied to the soil sample. A constant level "ground water" source was provided. A mercury-water manometer was used to measure the suction heads. Several thermistors were inserted into the soil sample to ascertain the advancement of the frozen layer and to calculate the thermal gradients.

Suction Head

Tests showed that it is possible to measure the suction head of a soil upon freezing. Also, tests indicate that the suction head, besides other factors, depends upon the rate of freezing of the soil sample, the soil properties, the suction height and also upon the surcharge on the sample.

Suction Coefficient

The suction coefficient or coefficient of thermo-osmotic permeability, k_s, can be calculated when the amount of soil heave, Δh, and the suction head, $\frac{P_s}{\gamma}$, is measured. These freezing tests prove that the suction force is an important geotechnical property of a soil. Currently, tests are under way to determine the suction properties of various soils upon freezing.

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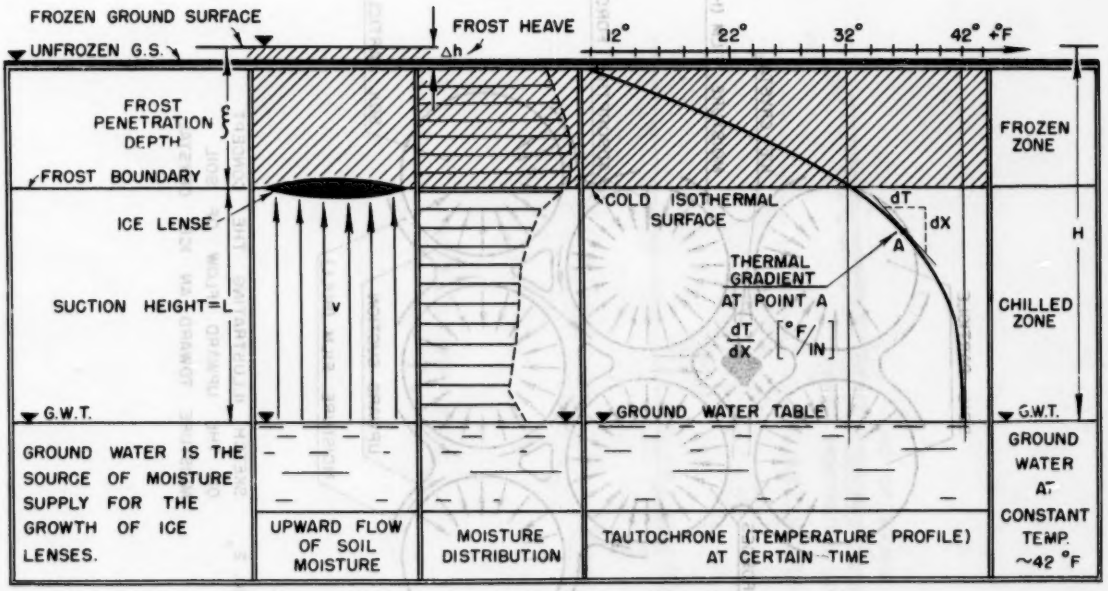

FIG. 1 SKETCH ILLUSTRATING THE CONCEPT OF UNIDIMENSIONAL UPWARD FLOW OF SOIL MOISTURE TOWARD THE FROST BOUNDARY (OR ICE LENSES) UPON FREEZING. OPEN SYSTEM.

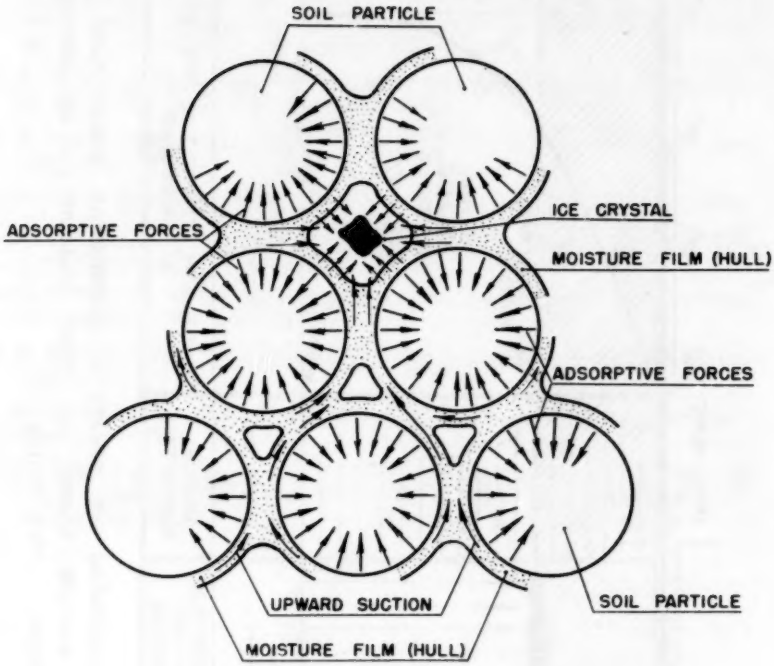

FIG. 2 SKETCH ILLUSTRATING THE CONCEPT OF THE UPWARD FLOW OF SOIL MOISTURE TOWARD AN ICE CRYSTAL.

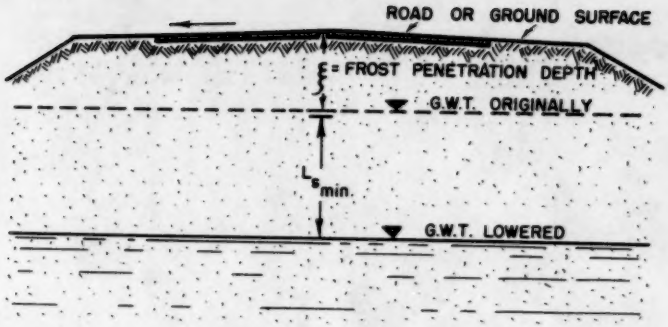

FIG. 3 ILLUSTRATING $L_{s_{min.}}$

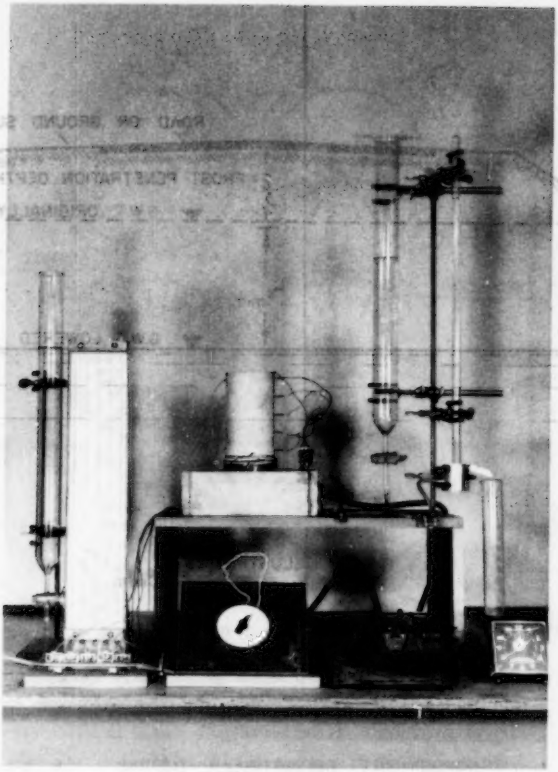

FIG. 4 TEST APPARATUS